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14. ABSTRACT  The central problem in any surveillance system is the data association problem of partitioning observations into tracks and false alarms. Over the last fifteen years and with support from AEOSR, a new approach has been developed based on the use of multi-dimensional assignment problem formulation and Lagrangian relaxation algorithms. (This approach is often called multiple frame assignments or MFA for short.) Four U. S. patents have now been issued for this work. What is more, based on this new technology, Lockheed Martin of Oswego, NY won the best of Breed Tracking Contest for the next upgrade to AWACS held at Hanscom AFB in Boston in 1996, and it has been chosen as the tracking system for the Navy's new multipurpose helicopter under the LAMPS program. Currently, it is a contender for national and ballistic missile defense in the Hercules Program funded by MDA Advanced Systems, for STSS Program as funded by the Department of the Air Force (in 2001 and 2002) and MDA in 2003.					
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FINAL TECHNICAL REPORT  
for  
OPTIMIZATION PROBLEMS IN  
MULTISENSOR AND MULTITARGET TRACKING  
AFOSR Grant Number F49620-00-1-0108

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March 12, 2004

# 1 INTRODUCTION AND OBJECTIVES

## 1.1 Overview and Executive Summary

The objectives of this research program have focused on optimization problems in multiple target tracking and sensor fusion. There are several such key problems that are evolving in DoD applications, namely the development of distributed tracking and data association algorithms across a network of platforms, new combinatorial optimization problems arising from merged measurements in radar tracking systems and cluster tracking of closely spaced objects, and bias estimation for multi-sensor and multi-platform tracking. In addition, improvements in the central problem in multiple target tracking, namely the data association problem formulated as a multidimensional assignment problem, continue to be of fundamental importance. Work in these four areas are described in the next subsection.

During the course of this funding, the tracking system based on AFOSR funded research has evolved into one of the nation's leading contenders for missile (Project Hercules at MDA for radar and the STSS Program Office for space based IR tracking) and air defense (JSSEO). These efforts have lead to transitions to Spectrum Astro in Phoenix, AZ and Northrop Grumman Space Technology in El Segundo, CA and potential transitions to air defense programs in addition to the previous transitions to AWACS and the Navy's Multipurpose helicopter program.

The research effort has supported eight graduate students, three of whom are now employed in the aerospace industry supporting DoD and Air Force efforts. In addition, recognition for the achievements are being received. Aubrey Poore is serving as a Subject Matter Expert to the Joint SIAP Systems Engineering Organization (JSSEO), has been awarded additional U.S. patents, and has recently received the 2004 Colorado State University Research Foundation Technology Transition Award.

## 1.2 STATUS OF EFFORT

The status of the current research program is summarized in this section. The individual topics are addressed in the following subsections.

### 1.2.1 Network-Centric Multiple Frame Assignments

An objective in this research program has been the development of distributed multiple frame data association algorithm that is comparable in quality to that of centralized tracking while managing communication loading and achieving a consistent or single integrated air picture. This has been "high-risk, high-payoff" problem that, if solved, would have a significant impact on multiple platform tracking. Here is a list of topics that surround this problem: (1) sensor location and registration biases (gridlock); (2) phenomenology issues such as multipath, unresolved closely spaced objects, and multisensor resolution problems; (3) single integrated air picture; (4) network communication loading (5) information transmitted over a network: measurements, tracklets, tracks (6) network communication

topology (new & legacy systems); (7) out-of-order, latent, and missing data; (8) scheduler for prioritizing targets; (9) development of a design that avoids pedigree problems.

A key component in maintaining consistency in the tracking picture is the use of a rule that “each platform is in charge of assigning its own measurements to the network tracks.”

Over the last three year, considerably progress in this work has been achieved with several architectures having been developed and tested. Sufficient progress on this effort has been made that it has now been transitioned to a Phase II SBIR at AFRL/SNAT with potential applications for the JSSEO for air defense and the Air Force’s “Network-Centric Collaborative Targeting” program funded out of the Big Safari office.

Publications 3 c, 3 e, 3 h address the basic approaches to this fundamental distributed tracking problem.

### **1.2.2 The Group-Assignment Problem**

The second large class of problems is that of the new data association problems (i.e., the problem of partitioning observations into tracks and false alarms) motivated by several different problems in multiple target tracking, namely cluster tracking including both group-cluster and pixel-cluster tracking, merged measurement problem for narrowband radar, and track-to-track fusion. The primary objective here has been the formulation of these problems as presented in Publications 3f, 3g, 3i, 3j, 3k, 3l, and 3n. Indeed, this subject has now matured to the point that it is the subject of the 2004-2006 renewal proposal.

### **1.2.3 Bias Estimation**

Sensor bias and navigation error estimation (hereafter called bias estimation) represent systematic unmodelled system or measurement errors. In single sensor environment, biases can lead to optimistic and diverging filters. In multi-sensor environments bias errors can lead to misassociation due to optimistic covariances or large residual biases, erratic stereo multiple model performance. There are various classification of the biases such as absolute vs. relative and sensor biases vs. navigation errors. Also, methods used to solve for these biases are based on truth targets or targets of opportunity in which data association is know or those in which data association is not known. In general, one must have targets with known data association spread over the field of regard to yield the most observable biases.

In funding from AFRL/SNAT, Numerica has formulated and tested a batch MAP estimation method based on nonlinear least squares assuming that the data association is known. The singular value decomposition is used to determine the bias roll-ups and the observable biases. The initial results (Publications 3m) are very promising with bias estimation leading to a performance of the multisensor tracking comparable to performance without biases.

The combination of data association with bias estimation is a very difficult problem

indeed; however, the diversity of targets over the field of regard make this problem particularly appealing. The problem is generally formulated as

$$\begin{array}{ll} \text{Minimize} & f(\omega) \\ \text{Subject To} & \omega \in \mathbb{R}^n \end{array} \quad (1)$$

where

$$\begin{array}{ll} f(\omega) \equiv \text{Minimize} & \sum_{(i,j) \in \mathcal{A}} c(\omega)_{ij} x_{ij}, \\ \text{Subject To} & \sum_{j \in \mathcal{A}(i)} x_{ij} \leq 1 \quad (i \in I), \\ & \sum_{i \in \mathcal{B}(j)} x_{ij} \leq 1 \quad (j \in J), \\ & x_{ij} \in \{0, 1\} \end{array} \quad (2)$$

This problem may have multiple minima, is nonsmooth in  $\omega \in \mathbb{R}^n$ , and, along with extensions to the multidimensional case, should remain a fundamentally important problem for some time to come. This research problem is one for a future investigation.

### 1.3 Improvements to the Multidimensional Assignment Algorithm

Early in this effort, algorithmic improvements to the existing Lagrangian relaxation algorithm were undertaken as in Publication 3a. The improvements are very significant. In the future, Numerica plans to undertake a systematic investigation along with an assessment of the ambiguity of the associations.

### 1.4 ACCOMPLISHMENTS/NEW FINDINGS

The central problem in any surveillance system is the data association problem of partitioning observations into tracks and false alarms. Over the last fifteen years and with support from AFOSR, a new approach has been developed based on the use of multidimensional assignment problem formulation and Lagrangian relaxation algorithms. (This approach is often called multiple frame assignments or MFA for short.) Four U. S. patents have now issued for this work. What is more, based on this new technology, Lockheed Martin of Owego, NY won the best of Breed Tracking Contest for the next upgrade to AWACS held at Hanscom AFB in Boston in 1996, and it has been chosen as the tracking system for the Navy's new multipurpose helicopter under the LAMPS program. Currently, it is a contender for national and ballistic missile defense in the Hercules Program funded by MDA Advanced Systems, for STSS Program as funded by the Department of

the Air Force (in 2001 and 2002) and MDA in 2003. Thus, appropriate recognition is being received.

At the same time, this collection of methods is providing the capability to achieve similar success in multiple platform tracking. Most importantly, an approach to the development of the all important *Network MFA* for multiple platform tracking has been developed, tested, and published. This research effort was suggested by Hanscom AFB. As such, new problems are being formulated or identified and algorithms are being developed to significantly enhance the nation's surveillance capability. This work has now been transitioned to Numerica in Fort Collins where the technology is being transitioned to industry such as Boeing, Lockheed Martin, Spectrum Astro, Northrop Grumman, and Logicon.

## 2 PERSONNEL SUPPORTED

- a. PI: Aubrey B. Poore
- b. Graduate Students: Keith Buck, Sabino Gadaleta, Suihua Lu, Sripriya Venkataraman, Xin Yan, Suihua Lu, Arif Albayrak, Fritz Obermeyer

## 3 PUBLICATIONS

- a. Aubrey B. Poore and Xin Yan, "Some Algorithmic Improvements in Multi-frame Most Probable Hypothesis Tracking," in Oliver E. Drummond, Editor, *Signal and Data Processing of Small Targets*, Proc. SPIE, 1999.
- b. Aubrey B. Poore, "Multidimensional Assignment Problems Arising in Multitarget and Multisensor Tracking," in Leonidas Pitsoulis and Panos M. Pardalos, Editors, *Nonlinear Assignment Problems*, Kluwer Academic Publishers B.V., Boston, 2000.
- c. Aubrey B. Poore, Suihua Lu, and Brian J. Suchomel, *Network MFA Tracking Architectures*, Proceedings of SPIE Conference on Small Targets 2001, Oliver E. Drummond Editor, August, 2001.
- d. Aubrey B. Poore, Suihua Lu, and Brian J. Suchomel, "Data Association Using Multiple Frame Assignments," in David L. Hall and James Llinas, Editors, *Handbook for Multi-sensor Data Fusion*, CRC Press, Inc. Boca Raton, FL, Chapter 11, 2001.
- e. Suihua Lu and Aubrey B. Poore, *Network-Centric Tracking Architectures*, in Sergiy Butenko, Robert Murphey, and Panos Pardalos, *Cooperative Control: Models, Applications and Algorithms*, Kluwer, 2002.
- f. S. Gadaleta and M. Klusman and A. Poore and Benjamin J. Slocumb, Multiple Frame Cluster Tracking, Proc. of AeroSense 2002, SPIE Vol. 4728, 2002, pp. 275-289.

- g. S. Gadaleta, A. Poore and Benjamin J. Slocumb, Some Assignment Problems Arising From Cluster Tracking, ORNL Workshop on Signal Processing, Communications and Chaotic Systems: A Tribute to Rabinder N. Madan, June 20, 2002, YBS Publishing.
- h. Suihua Lu, Aubrey B Poore, Brian J Suchomel, Network MFA Tracking Architectures, Proceedings of the Fifth International Conference on Information Fusion, 2002. Fusion 2002, pages 520-526.
- i. A. B. Poore and S. Gadaleta, The cluster assignment problem, Workshop on Multiple Hypothesis Tracking: A Tribute to Samuel Blackman, May 30, 2003, San Diego, California, 2003.
- j. S. Gadaleta and A. B. Poore and B. J. Slocumb, Single-frame cluster MFA tracking, Proceedings of the American Control Conference, Denver, Colorado, June 2003, 1242-1247.
- k. Sabino Gadaleta, Benjamin Slocumb, and Aubrey Poore, Pixel-Cluster Decomposition Tracking for Multiple IR-Sensor Surveillance, in Oliver E. Drummond, ed., Proceedings of SPIE Conference on Small Targets, SPIE, August, 2003.
- l. Sabino Gadaleta and Aubrey Poore, The Group Assignment Problem, in Oliver E. Drummond, ed., Proceedings of SPIE Conference on Small Targets, SPIE, August, 2003.
- m. Aubrey Poore, Shawn Herman, Brian Suchomel, Benjamin Slocumb, Fritz Obermeyer, Batch ML and MAP estimation with process noise, in Oliver E. Drummond, ed., Proceedings of SPIE Conference on Small Targets, SPIE, August, 2003.
- n. Aubrey B Poore and Sabino Gadaleta, New Data Association Problems in Multiple Target Tracking, in Donald Grundel, Robert Murphey, and Panos Pardalas, *Cooperative Control and Optimization*, Kluwer, 2004.

## 4 INTERACTIONS/TRANSITIONS

- a. **Participation/presentations at meetings, conferences, seminars, etc.**
  - i. Multiple Frame Assignment Approach to Tracking, Northrop Grumman, May, 2000.
  - ii. Decentralized Correlation for Multiple Sensor Integration, Hanscom AFB, June 20, 2000
  - iii. Centralized Tracking Using Multiple Frame Assignments, Mitre in Boston, MA, June 21-22, 2000

- iv. Participation in Joint Composite Tracking Network for ONR/BMDO including Talk Washington, DC (May 26 1999, August 18 1999, September 22 1999, December 15, 1999)
- v. Participation in Joint Composite Tracking Network for ONR/BMDO including Talks Columbia, MD (Feb. 9, June 11-13, April 10-12, August 22-23)
- vi. Participation in Project Hercules Advanced Concepts Panel including Talks Rosslyn, VA (April 13-14, June 14-15, August 22-23)
- vii. Multiple Frame Assignments: A Review for Project Hercules, Crystal City, VA., MSF Panel for Project Hercules.
- viii. Feature Aided Tracking, Target Recognition Branch, AFRL/SN, Wright Research Site, August 19-20, 2000.
- ix. Network-Centric Multiple Frame Data Association For Tracking Air and Ground Targets, AFRL/AFOSR Sponsored Workshop at University of Florida, Dec. 3, 2001.
- x. Network-Centric Multiple Frame Data Association, JCTN/BMD Benchmark Meetings at APL in Columbia, MD (Oct. and Nov. of 2000 and Jan., April, August of 2001)
- xi. Multiple Target Tracking for SBIRS Low (Aerospace Corporation (May 2001), Logicon in San Pedro, CA (June, 2001), Northrop Grumman at BWI (July and October 2001), Spectrum Astro in Gilbert, AZ (bimonthly)
- xii. Participation in Project Hercules Advanced Concepts Panel including Talks Rosslyn, VA and MIT LL (Nov, 2000 and April, 2001)
- xiii. Network-Centric Multiple Frame Tracking, SPIE Conference, San Diego, August, 2001.
- xiv. Suihua Lu and Aubrey B Poore, Network-Centric Tracking, AFOSR Sponsored PI Meeting, Minnowbrook, NY
- xv. Suihua Lu and Aubrey B. Poore, Network-Centric Tracking Architectures, AFRL/AFOSR Sponsored Workshop at University of Florida, Nov., 2002.
- xvi. Sabino Gadaleta, Multiple Frame Cluster Tracking Assignment Problems, SPIE Meeting, Orlando, FL, April, 2002.
- xvii. Multiple Target Tracking for SBIRS Low, Monthly at Spectrum Astro in Phoenix, AZ
- xviii. Participation in Project Hercules Advanced Concepts Panel including Talks Rosslyn, VA and Raytheon (April, 2002 and August, 2002)
- xix. Network-Centric Multiple Frame Tracking, Fusion 2002 Conference, Annapolis, MD, July, 2002.
- xx. Network MFA, Project Hercules Review, at MIT/LL in October, 2002.

- xxi. Network MFA, Project Hercules Tracking TIM, at Raytheon, El Segundo, CA, July, 2002
- xxii. SBIRS Low Tracker Development, at Baltimore, MD (Feb, 2002) ; Gilbert, AZ (May 2002), El Segundo, CA (Dec, 2002)
- xxiii. Track Matching, MDA BMD Benchmark Meeting, Washington, DC Nov., 2002.
- xxiv. MFA Tracker Performance, MDA BMD Benchmark Meeting, Washington, DC Nov., 2002.
- xxv. The Group Assignment Problem, AFOSR PI Retreat, Estes Park, May, 2003
- xxvi. Batch ML/MAP Estimation with Process Noise, ONR Workshop, San Diego, May, 2003
- xxvii. Sabino Gadaleta, Benjamin Slocumb, and Aubrey Poore, Pixel-Cluster Decomposition Tracking for Multiple IR-Sensor Surveillance, SPIE Conference on Small Targets, August, 2003.
- xxviii. Sabino Gadaleta and Aubrey Poore, The Group Assignment Problem, SPIE Conference on Small Targets, August, 2003.
- xxix. Aubrey Poore, Shawn Herman, Brian Suchomel, Benjamin Slocumb, Fritz Obermeyer, Batch ML and MAP estimation with process noise, SPIE Conference on Small Targets, August, 2003.

**b. Consultative and Advisory Functions**

- i. Multiple Sensor Fusion Panel for Project Hercules at BMDO (2000 - 2004).
- ii. Workshop on Information Fusion May, 2000 at AFRL- Rome, NY. Funded by AFRL-Rome.
- iii. Joint Composite Tracking Network (JCTN) Benchmark Team (1998 - 2001). Funded by BMDO.
- iv. JSSEO Subject Matter Expert on Tracking and Combat Identification (2003 - 2004).

**c. Transitions**

**i. Transition: Numerica, Inc.**

Numerica, Inc., a Colorado Corporation, is a small business in Fort Collins, CO that is engaged in basic research, software development, and engineering services, especially in surveillance. Aubrey B. Poore is President. In January of 1999, Numerica completed negotiations with Colorado State University Research Foundation (CSURF) to take out an exclusive license on the four U. S. Patents, software, and tracking technology developed by Aubrey Poore at Colorado State University (CSU) (past, present, and future) for the purpose of licensing the tracking technology to industry.

**ii. Transition: Mitre**

Numerica is transitioning a state-of-the-art tracking system for *air and missile defense* to Mitre. One of the fundamental changes here is that the problems are truly of large scale, e.g., thirty different platforms and hundreds of sensors, and must process a variety of sensors such as radar and ESA. Much of this work is to modify the tracking system to accept and process Mitre's data. This transition continues in the years 1999 - 2001.

John J. Roberts  
Project Leader, 6121  
Mitre Corporation  
Bedford, MA  
Phone: 781-377-4983  
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E-Mail: [jjrobert@mitre.org](mailto:jjrobert@mitre.org)

**iii. Transition: SBIRS Low (Now STSS)**

In a rapid and advanced development program funded by Spectrum Astro of Gilbert, AZ, Numerica is developing a state-of-the-art tracking system for a satellite based infrared system for tracking missiles in midcourse. The SBIRS Low program has been an Air Force Project which will move to BMDO in 2002, but will still be administered by the Department of the Air Force at the Los Angeles AFB. This effort is part of a national competition between Spectrum Astro/Northrop Grumman and TRW/Raytheon. The contact person is

Ben Overall  
Spectrum Astro  
Gilbert, AZ  
Phone: 480.892.8200  
E-Mail: [ben.overall@spectastro.com](mailto:ben.overall@spectastro.com)

**iv. Transition: Project Hercules, MDA/AS**

In a rapid and advanced development program funded by MDA for Project Hercules, Numerica is developing a state-of-the-art tracking system for radar based tracking of missiles for both national and theater missile defense. While SBIRS Low is for satellite based IR sensors, this program focuses on radar based systems located on the ground, on the sea, and in the air. As part of this effort, Numerica has transitioned its radar missile tracking system to MIT Lincoln Labs in Boston and Xontech (now Northrop Grumman) in Huntsville in 2003.

Steve Bravy

MDA/AS  
Washington, DC  
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## 5 NEW DISCOVERIES, INVENTIONS, OR PATENTS

Patents continue to emanate from the basic research supported by AFOSR. Of the four patents listed below, three have issued with one, which has been revised and re-submitted to correct the typing errors, to issue in late 2001 or early 2002. The first and second patents cover Lagrangian relaxation approaches to data association problems in fusion and tracking and the third patent covers linear programming relaxations, and the fourth updated the third with 21 claims on linear programming approaches.

### a. NEW DISCOVERIES/INVENTIONS:

The inventions as embodied in the U.S. Patent below contains various approaches to data association problems based on linear programming relaxations and contains a description of the variable depth sliding window.

### b. PATENTS ISSUED IN 2002

Aubrey B. Poore, Jr., Method and System for Tracking Multiple Regional Objects by Multi-Dimensional Relaxation, U.S. Patent Number 6,404,380 B2, Issued 11 June 2002. (Assignee: Colorado State University Research Foundation, Fort Collins, CO)

### d. PREVIOUSLY ISSUED PATENTS

Thomas N. Barker, Joseph A. Persichetti, Aubrey B. Poore, Jr., and Nenad Rujavec, Method and System for Tracking Multiple Regional Objects, US Patent Number 5406289, issued 11 April 1995. (Assignees: IBM, Owego, NY; Colorado State University Research Foundation, Fort Collins, CO)

Aubrey B. Poore, Jr., Method and System for Tracking Multiple Regional Objects by Multi-Dimensional Relaxation, CIP, US Patent Number 5537119, issued on 16 July 1996. (Assignee: Colorado State University Research Foundation, Fort Collins, CO)

Aubrey B. Poore, Jr., Method and System for Tracking Multiple Regional Objects by Multi-Dimensional Relaxation, CIP, U. S. Patent Number 5,959,574, issued on September 28, 1999. (Assignee: Colorado State University Research Foundation, Fort Collins, CO)

## 6 HONORS/AWARDS

- a. Name of Award: **Colorado State University Research Foundation Technology Transfer Award, formerly "Researcher of the Year"**.

Year Received: **2004**

Honor/Award Recipient(s): Aubrey B. Poore

Awarding Organization: Colorado State University and Colorado State University Research Foundation.

- b. Name of Award: **The 1999 Colorado State University Alumni Association Distinguished Faculty Award**. (The purpose of this award is to recognize one faculty member each year for their individual contributions to the goal of excellence at Colorado State University. The award is given to a current Colorado State University faculty member, not necessarily a Colorado State University graduate, who has demonstrated excellence in teaching, research, and/or service.)

Year Received: **1999**

Honor/Award Recipient(s): Aubrey B. Poore

Awarding Organization: Colorado State University Alumni Association

- c. Name of Award: **The Burlington Northern Faculty Achievement Award for Research and Graduate Education**

Year Received: 1990. (This was the eleventh such award for all of Colorado State University.)

Honor/Award Recipient(s): Aubrey B. Poore

Awarding Organization: Colorado State University

- d. Aubrey Poore continues to server as Associate Editor of *Computational Optimization and Applications*.